

Z' boson signal at Tevatron and LHC in a 331 model

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Abstract

We analyse the possibilities to detect a new Z' boson in di-electron events at Tevatron and LHC in the framework of the 331 model with right-handed neutrinos. Using $p\bar{p}$ collision data collected by the CDF II detector at Fermilab Tevatron, we find that the 331 Z' boson is excluded with masses below 920 GeV. For an integrated luminosity of $100fb^{-1}$ at LHC, and considering a central value $M_{Z'} = 1500$ GeV, we obtain the invariant mass distribution in the process $pp \rightarrow Z' \rightarrow e^+e^-$, where a huge peak, corresponding to 800 signal events, is found above the SM background. The number of di-electron events vary from 10000 to 1 in the mass range of $M_{Z'} = 1000 - 5000$ GeV.

1 Introduction

In many extensions of the Standard Model (SM), new massive and neutral gauge bosons, called Z' , are predicted [1]. The detection of a Z' resonance have became in a matter of high priority in particle physics, which could reveal many features about the underlying unified theory. Indirect search for these neutral bosons have been carried out at LEP, through mixing with the Z boson [2]. Direct Z' production have been currently proved at the Tevatron [3, 4]. The discovery potential for Z' particles have been explored at the forthcoming Large Hadron Collider (LHC) [5] in the $M_{Z'} \approx 1 - 5$ TeV range. The search for this particle have also been explored in the planned International Liner Collider (ILC) [6].

There are many theoretical models which predict a Z' mass in the TeV range, where the most popular are the E_6 motivated models [1, 7], the Left-Right Symetric Model (LRM) [8], the Z' in Little Higgs scenario [9] and the Sequential Standard Model (SSM), which has heavier couplings than those of the SM Z boson. Searching for Z' in the above models has been widely studied in the literature [1] and applied at LEP2, Tevatron and LHC. On the other hand, the models with gauge symmetry $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$, also called 331 models [10, 11, 12], arise as an interesting alternative with Z' boson and many well-established motivations. First of all, from the cancellation of chiral anomalies [13] and

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asymptotic freedom in QCD, the 3-3-1 models can explain why there are three fermion families. Secondly, since the third family is treated under a different representation, the large mass difference between the heaviest quark family and the two lighter ones may be understood [14]. Thirdly, the models have a scalar content similar to the two Higgs doublet model (2HDM), which allow to predict the quantization of electric charge and the vectorial character of the electromagnetic interactions [15, 16]. Also, these models contain a natural Peccei-Quinn symmetry, necessary to solve the strong-CP problem [17, 18]. Finally, the model introduces new types of matter relevant to the next generations of colliders at the TeV energy scales, which do not spoil the low energy limits at the electroweak scale.

Although the theoretical and phenomenological features associated to the Z' boson is widely described in the literature [1]-[6], there are few studies at Tevatron and LHC colliders of the Z' boson in the framework of the 331 models [19]. In this work we search for Z' bosons in dielectron events produced in $p\bar{p}$ and pp collisions for Tevatron and LHC colliders, respectively in the framework of the 331 model with right-handed neutrinos, which we denote as the Foot-Long-Truan (FLT) model [12].

2 The 331 spectrum

The fermionic structure is shown in Tab. 1 where all leptons transforms as $(\mathbf{3}, \mathbf{X}_\ell^L)$ and $(\mathbf{1}, \mathbf{X}_\ell^R)$ under the $(SU(3)_L, U(1)_X)$ sector, with \mathbf{X}_ℓ^L and (\mathbf{X}_ℓ^R) the $U(1)_X$ generators associated with the left- and right-handed leptons, respectively; while the quarks transforms as $(\mathbf{3}^*, \mathbf{X}_{q_m^*}^L)$, $(\mathbf{1}, \mathbf{X}_{q_m^*}^R)$ for the first two families, and $(\mathbf{3}, \mathbf{X}_{q_3}^L)$, $(\mathbf{1}, \mathbf{X}_{q_3}^R)$ for the third family, each one with its $U(1)_X$ values for the left- and right-handed quarks. The quantum numbers \mathbf{X}_ψ for each representation are given in the third column from Tab. 1, where the electric charge is defined by

$$Q = T_3 + \beta T_8 + XI, \quad (1)$$

with $T_3 = 1/2 \text{diag}(1, -1, 0)$, $T_8 = (1/2\sqrt{3}) \text{diag}(1, 1, -2)$. The most popular cases are when $\beta = -1/\sqrt{3}$ and $-\sqrt{3}$, where the first case contains the Foot-Long-Truan model (FLT) [12] and the second contains the Pisano-Pleitez-Frampton model (PPF) [10, 11].

For the scalar sector, we introduce the triplet field χ with vacuum expectation value (VEV) $\langle \chi \rangle^T = (0, 0, \nu_\chi)$, which induces the masses to the third fermionic components. In the second transition it is necessary to introduce two triplets ρ and η with VEV $\langle \rho \rangle^T = (0, \nu_\rho, 0)$ and $\langle \eta \rangle^T = (\nu_\eta, 0, 0)$ in order to give masses to the quarks of type up and down respectively [20].

In the gauge boson spectrum associated with the group $SU(3)_L \otimes U(1)_X$, we are just interested in the physical neutral sector that corresponds to the photon, Z , and Z' , which are written in terms of the electroweak basis for any β as [21]

representation	Q_ψ	X_ψ
$q_{m^*L} = \begin{pmatrix} d_{m^*} \\ -u_{m^*} \\ J_{m^*} \end{pmatrix}_L \mathbf{3}^*$	$\begin{pmatrix} -\frac{1}{3} \\ \frac{2}{3} \\ \frac{1}{6} + \frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X_{q_{m^*}}^L = \frac{1}{6} + \frac{\beta}{2\sqrt{3}}$
$d_{m^*R}; u_{m^*R}; J_{m^*R} : \mathbf{1}$	$-\frac{1}{3}; \frac{2}{3}; \frac{1}{6} + \frac{\sqrt{3}}{2}\beta$	$X_{d_{m^*}, u_{m^*}, J_{m^*}}^R = -\frac{1}{3}, \frac{2}{3}, \frac{1}{6} + \frac{\sqrt{3}}{2}\beta$
$q_{3L} = \begin{pmatrix} u_3 \\ d_3 \\ J_3 \end{pmatrix}_L : \mathbf{3}$	$\begin{pmatrix} \frac{2}{3} \\ -\frac{1}{3} \\ \frac{1}{6} - \frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X_{q^{(3)}}^L = \frac{1}{6} - \frac{\beta}{2\sqrt{3}}$
$u_{3R}; d_{3R}; J_{3R} : \mathbf{1}$	$\frac{2}{3}; -\frac{1}{3}; \frac{1}{6} - \frac{\sqrt{3}\beta}{2}$	$X_{u_3, d_3, J_3}^R = \frac{2}{3}, -\frac{1}{3}, \frac{1}{6} - \frac{\sqrt{3}\beta}{2}$
$\ell_{jL} = \begin{pmatrix} \nu_j \\ e_j \\ E_j^{-Q_1} \end{pmatrix}_L : \mathbf{3}$	$\begin{pmatrix} 0 \\ -1 \\ -\frac{1}{2} - \frac{\sqrt{3}\beta}{2} \end{pmatrix}$	$X_{\ell_j}^L = -\frac{1}{2} - \frac{\beta}{2\sqrt{3}}$
$e_{jR}; E_{jR}^{-Q_1}$	$-1; -\frac{1}{2} - \frac{\sqrt{3}\beta}{2}$	$X_{e_j, E_j}^R = -1, -\frac{1}{2} - \frac{\sqrt{3}\beta}{2}$

Table 1: *Fermionic content for three generations. We take $m^* = 1, 2$ and $j = 1, 2, 3$*

$$\begin{aligned}
A_\mu &= S_W W_\mu^3 + C_W \left(\beta T_W W_\mu^8 + \sqrt{1 - \beta^2 T_W^2} B_\mu \right), \\
Z_\mu &= C_W W_\mu^3 - S_W \left(\beta T_W W_\mu^8 + \sqrt{1 - \beta^2 T_W^2} B_\mu \right), \\
Z'_\mu &= -\sqrt{1 - \beta^2 T_W^2} W_\mu^8 + \beta T_W B_\mu,
\end{aligned} \tag{2}$$

where the Weinberg angle is defined as [21]

$$S_W = \sin \theta_W = \frac{g_X}{\sqrt{g_L^2 + (1 + \beta^2) g_X^2}} \tag{3}$$

and g_L, g_X correspond to the coupling constants of the groups $SU(3)_L$ and $U(1)_X$, respectively. It is to note that the Z and Z' bosons in Eq. (2) are not truly mass eigenstates, but there is a $Z - Z'$ mixing angle that rotate the neutral sector to the physical Z_1 and Z_2 bosons. However, the hadronic reactions are much less sensitive to the $Z - Z'$ mixing than lepton reactions [1]. Thus, the $Z - Z'$ mixing can be neglected and we identify the Z and Z' bosons as the physical neutral bosons.

3 Neutral Couplings and the Cross Section

Using the fermionic content from Tab. 1, we obtain the neutral coupling for the SM fermions [21]

$$\mathcal{L}_D^{NC} = \frac{g_L}{2C_W} [\bar{f}\gamma_\mu (g_v^f - g_a^f\gamma_5) f Z^\mu + \bar{f}\gamma_\mu (\tilde{g}_v^f - \tilde{g}_a^f\gamma_5) f Z^\mu], \quad (4)$$

where f is $U = (u, c, t)$, $D = (d, s, b)$ for up- and down-type quarks, respectively and $N = (\nu_e, \nu_\mu, \nu_\tau)$, $L = (e, \mu, \tau)$ for neutrinos and charged leptons, respectively. The vector and axial-vector couplings of the Z boson are the same as the SM Z -couplings

$$\begin{aligned} g_v^{U,N} &= \frac{1}{2} - 2Q_{U,N}S_W^2, & g_a^{U,N} &= \frac{1}{2}, \\ g_v^{D,L} &= -\frac{1}{2} - 2Q_{D,L}S_W^2, & g_a^{D,L} &= -\frac{1}{2}, \end{aligned} \quad (5)$$

with Q_f the electric charge of each fermion given by Tab. 1; while the corresponding couplings to Z' are given by [22]

$$\begin{aligned} \tilde{g}_{v,a}^{U,D} &= \frac{C_W}{2\sqrt{1-\beta^2T_W^2}} \left[\frac{1}{\sqrt{3}} \left(\text{diag}(1, 1, -1) + \frac{\beta T_W^2}{\sqrt{3}} \right) \pm 2Q_{U,D}\beta T_W^2 \right], \\ \tilde{g}_{v,a}^{N,L} &= \frac{C_W}{2\sqrt{1-\beta^2T_W^2}} \left[\frac{-1}{\sqrt{3}} - \beta T_W^2 \pm 2Q_{N,L}\beta T_W^2 \right], \end{aligned} \quad (6)$$

where the plus sign (+) is associated with the vector coupling \tilde{g}_v , and the minus sign (−) with the axial coupling \tilde{g}_a . The above equations are written for $\beta = -1/\sqrt{3}$, which corresponds to the FLT model. On the other hand, the differential cross section for the process $pp(p\bar{p}) \rightarrow Z' \rightarrow f\bar{f}$ is given by [1]

$$\frac{d\sigma}{dMdydz} = \frac{K(M)}{48\pi M^3} \sum_q P[B_q G_q^+(1+z^2) + 2C_q G_q^- z], \quad (7)$$

where $M = M_{ff}$ is the invariant final state mass, $z = \cos\theta$ the scattering angle between the initial quark and the final lepton in the Z' rest frame, $K(M) \simeq 1.3$ contains leading QED corrections and NLO QCD corrections, $y = 1/2 \log[(E + p_z)/(E - p_z)]$ the rapidity, E the total energy, p_z the longitudinal momentum, $P = s^2/[(s - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2]$, \sqrt{s} the collider CM energy, $M_{Z'}$ and $\Gamma_{Z'}$ the Z' mass and total width, respectively. The parameters $B_q = [(\tilde{g}_v^q)^2 + (\tilde{g}_a^q)^2][(\tilde{g}_v^f)^2 + (\tilde{g}_a^f)^2]$ and $C_q = 4(\tilde{g}_v^q\tilde{g}_a^q)(\tilde{g}_v^f\tilde{g}_a^f)$ contains the couplings from Eq. (6) for the initial quarks q and the final fermions f , while the parameter $G_q^\pm = x_A x_B [f_{q/A}(x_A) f_{\bar{q}/B}(x_B) \pm f_{q/B}(x_B) f_{\bar{q}/A}(x_A)]$ contains the Parton Distribution Functions (PDFs) $f(x)$, and the momentum fraction $x = Me^{\pm y}/\sqrt{z}$. We can consider the Narrow Width Approximation (NWA), where the relation $\Gamma_{Z'}/M_{Z'}$ is very small, so that the contribution to the cross section can be separated into the Z' production cross section $\sigma(pp(\bar{p}) \rightarrow Z')$ and the fermion branching fraction of the Z' boson $Br(Z' \rightarrow f\bar{f})$

$$\sigma(pp(\bar{p}) \rightarrow f\bar{f}) = \sigma(pp(\bar{p}) \rightarrow Z')Br(Z' \rightarrow f\bar{f}), \quad (8)$$

From the analysis of reference [22] we can estimate that $\Gamma_{Z'}^2/M_{Z'}^2 \approx 1 \times 10^{-4}$. Thus, the NWA is an appropriate approximation in our calculations.

4 Z'_{FLT} at Tevatron

A recent report of a search for electron-positron events in the invariant mass range 150 – 950 GeV collected by the CDF II detector at the Fermilab Tevatron [4] have excluded possible Z' particles for five different models: the Z'_η , Z'_χ , Z'_ψ and Z'_I bosons from the E_6 model, and the Z'_{SM} from the Sequential Standard Model (SSM). We use the data from reference [4] in order to bound the Z'_{FLT} mass from the FLT 331 model. Basically, the CDF II is an azimuthally and forward-backward symmetric particle detector, where the most important features and kinematical cuts are [4]

- $p\bar{p}$ collisions at C.M. energy $\sqrt{s} = 1.96$ TeV,
- Integrated luminosity $L = 1.3fb^{-1}$,
- Central Calorimeter in the $|\eta| \leq 1.1$ range and plug Calorimeters in the $1.2 \leq |\eta| \leq 3.6$ range,
- Transverse energy cut $E_T \geq 25$ GeV.

For this study, we use the CalcHep package [23] in order to simulate $p\bar{p} \rightarrow e^+e^-$ events with the above kinematical criteria. Using a non-relativistic Breit-Wigner function and the CTEQ6M PDFs [24], we perform a numerical calculation with the following parameters

$$\alpha^{-1} = 128.91, \quad S_W^2 = 0.223057, \quad \Gamma_{Z'} = 0.02M_{Z'}, \quad (9)$$

where the total width $\Gamma_{Z'} = 0.02M_{Z'}$ is estimated from the analysis performed in the reference [22] for the FLT model. Fig. 1, shows the 95% CL on $\sigma(pp(\bar{p}) \rightarrow Z')Br(Z' \rightarrow f\bar{f})$ extracted from reference [4] which does not show any significant signal above the SM prediction. In the same plot, we show the corresponding falling prediction for the Z' cross section in the FLT model assuming that only SM fermions participate in the Z' decay. For small invariant masses, the 331 prediction exceeds the 95% CL bound. A bound is found at $M_{Z'} = 920$ GeV, where both curves cross. Table 2 shows lower bounds for different models at Tevatron, where the 331 model exhibit a bigger bound than the E_6 Z' bosons.

5 Z'_{FLT} at LHC

The design criteria of ATLAS at LHC could reveal Z' signal at the TeV scale. The expected features of the detector are [5]

- pp collisions at C.M. energy $\sqrt{s} = 14$ TeV,

$Z' - Model$	Z'_{FLT}	Z'_{SM}	Z'_{ψ}	Z'_{η}	Z'_{χ}	Z'_I
95% C.L. Bound (GeV)	920	923	822	891	822	729

Table 2: 95% CL lower bounds at Tevatron on the Z' mass for the FLT 331 model, the SSM, and Z' bosons from E_6 models

- Integrated luminosity $L = 100fb^{-1}$,
- Pseudorapidity below $|\eta| \leq 2.2$
- Transverse energy cut $E_T \geq 20$ GeV.

The left plot in Fig. 2 shows the invariant mass distribution for the dielectron system as final state, where we have chosen a central value $M_{Z'} = 1500$ GeV, which is a typical lower bound for FLT models from low energy analysis at the Z -pole [25], and which falls into the expected detection range for LHC. The right plot in the same figure shows the number of events for the expected luminosity of $100fb^{-1}$. We also calculate the SM Drell-Yan spectrum in both plots with the same kinematical conditions, where we can see a huge peak above the SM background in the resonance with about 800 signal events.

On the other hand, we calculate the cross section for the same leptonic channel as a function of $M_{Z'}$, as shown in the left plot in Fig. 3. The right plot shows the number of events, where the SM background is found to be essentially negligible for all the selected range. For $M_{Z'} = 1$ TeV, we get a huge number of events, corresponding to 10000 signal events, while at the large mass limit $M_{Z'} = 5$ TeV, we find just 1 event per year.

6 Conclusions

In the framework of the FLT 331 model, we have analyzed the Z' production assuming the design criteria of CDF and ATLAS detectors at Tevatron and LHC colliders, respectively. Using recent data from CDF collaboration, the FLT Z' is excluded at 95% CL with masses below 920 GeV. For an integrated luminosity of $100fb^{-1}$ in LHC and considering a central value of $M_{Z'} = 1500$ GeV, we find a narrow resonance with 800 signal events above the SM background. If the Z' mass increases, the number of events decreases from 10000 to 1 signal event in the $M_{Z'} = 1000 - 5000$ GeV range.

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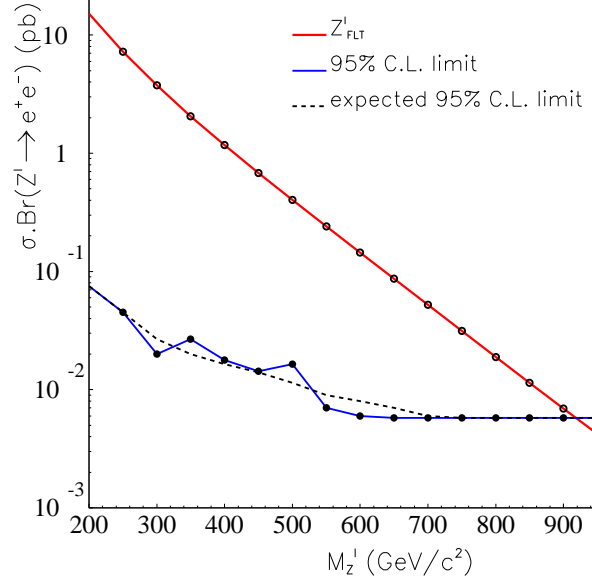


Figure 1: The limit on σBr as a function of the dielectron mass for the 95% CL experimental data in Tevatron and the prediction of the 331 FLT model. Both plots cross at the bound 920 GeV.

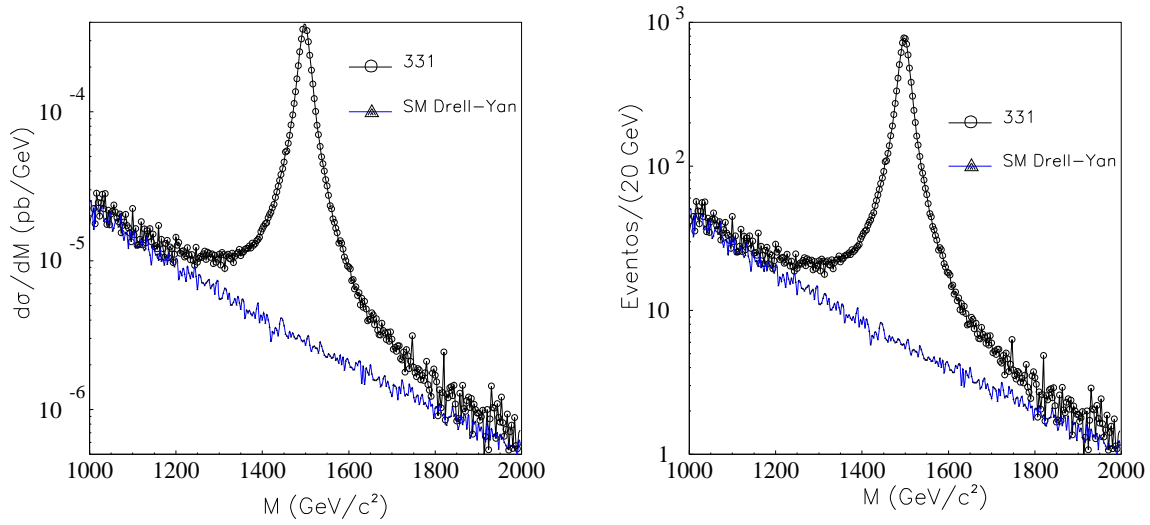


Figure 2: The left plot shows the cross section distribution as a function of the invariant final state mass for $M_{Z'} = 1500$ GeV in LHC. The right plot shows the number of events.

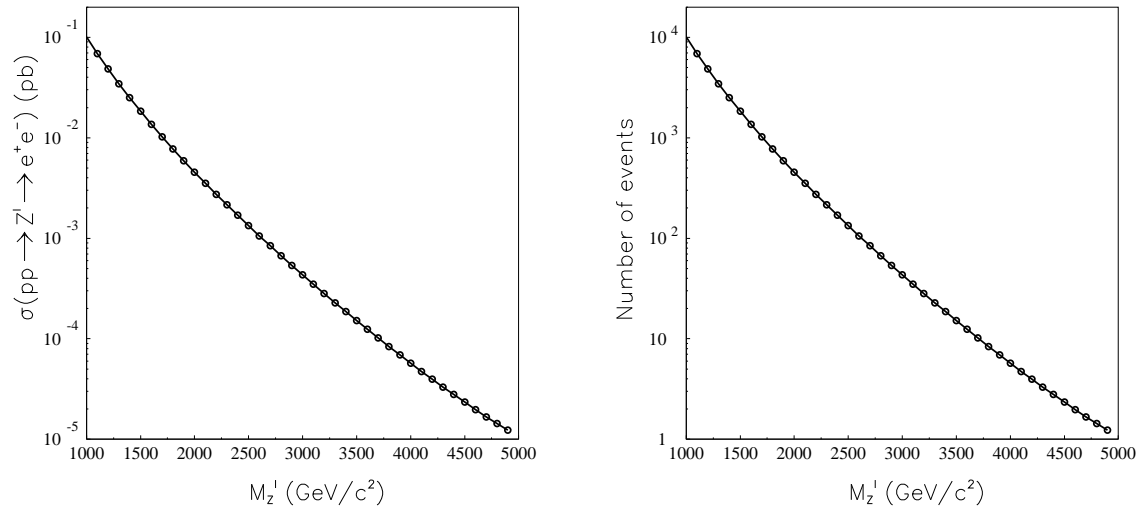


Figure 3: The left plot shows the cross section as a function of $M_{Z'}$ in LHC. The right plot shows the number of events.